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(54) Matching hardcopy color to display color.

(57) A method for matching hardcopy color to display color for registered-dot ink-jet copies. Video RGB is converted into chromaticity coordinates in XYZ color space. An explicit solution is achieved by defining a new MSW color space which restricts the hardcopy colors to some percentage of one of the binary Mixtures of inks, some percentage of one of the Single inks, and some percentage of paper White. The color data in XYZ space is converted to MSW space and unreachable colors are mapped into reachable colors. Correction for hardcopy non linearities is accomplished by considering the interaction among the inks by using a coverage ratio to correct for color shifts. The MSW values are, thus, converted to CMY values which are sent to an appropriate dithering algorithm for conversion into dots on the paper.

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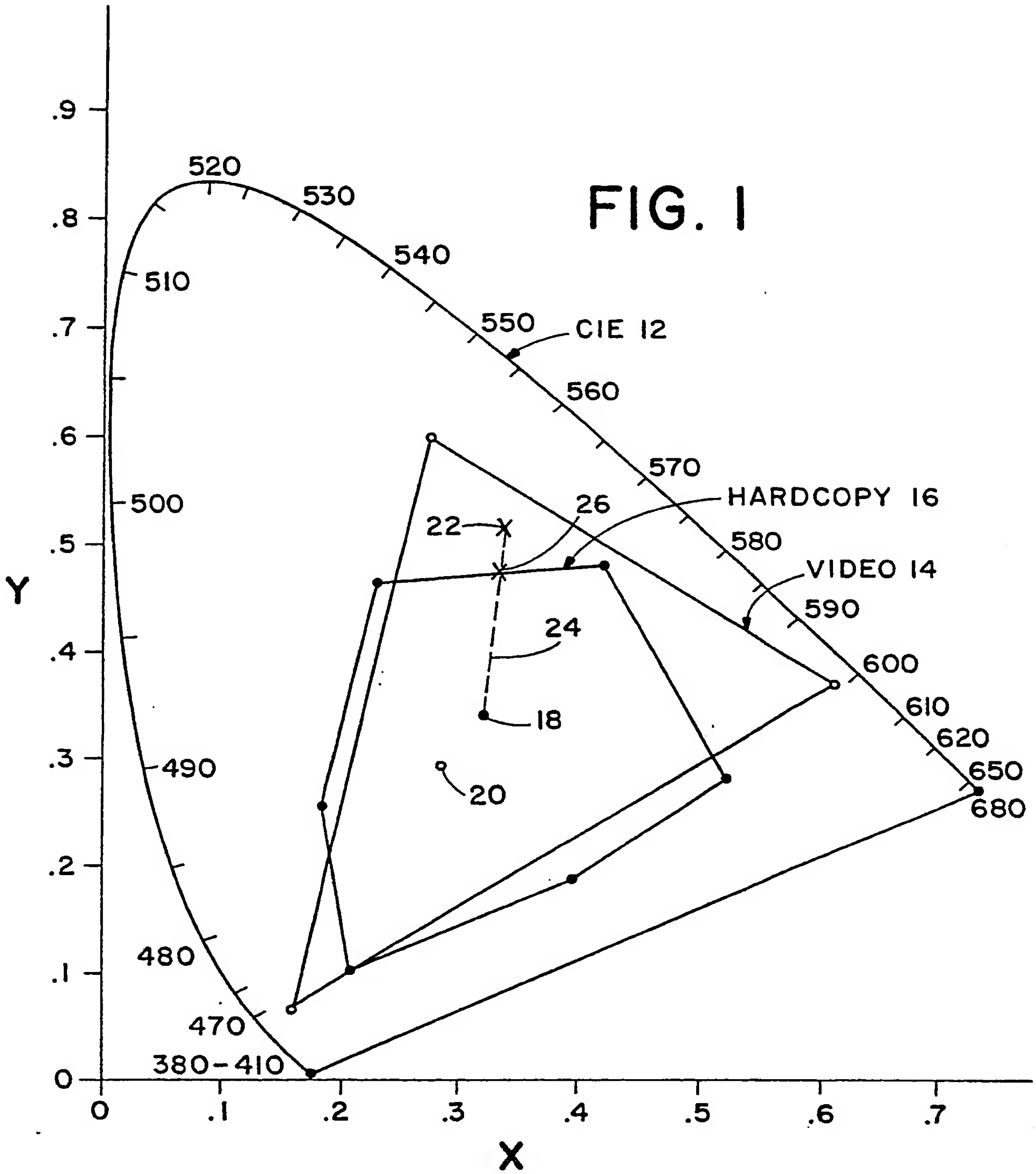
FIG. 1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Y
0
.1
.2
.3
.4
.5
.6
.7
X
520
530
540
550
560
570
580
590
600
610
620
650
680
510
500
490
480
470
380-410
CIE 12
HARDCOPY 16
VIDEO 14
26
22
24
18
20

MATCHING HARDCOPY COLOR TO DISPLAY COLOR

Background of the Invention

Field of the Invention

The present invention relates to transformation of a color image from one color space to another, and more particularly to an efficient algorithm for performing the transformation of color of known composition in terms of the intensities of video red, green and blue phosphors into the necessary densities of cyan, magenta, yellow and black inks, as deposited by a display device, to yield a visual match between the color so produced on hardcopy and the video color.

Description of the Prior Art

There are situations where a hardcopy of a color video display should match that display in color. Two examples are renderings of digitized photographs and proofing copies for a graphic artist's work station, and it is considered by people working in hardcopy technology that a color match is desirable generally.

The defining data can have a number of different forms. Images taken from photographic sources exist as values in RGB, based upon a set of color separation filters which may or may not be clearly defined. Images generated originally on a graphics display exist as values in the RGB drive intensities for the set of phosphors, such as a NTSC standard phosphor set, used in creating them, the parameters of which set may or may not be known. Images generated by a computer are based on an arbitrary set of RGB definitions which may or may not be known. Thus no single set of primaries can be defined for all the needed transformations.

For a video display color is produced by adding light from the various phosphors, while for a hardcopy device color is produced by subtracting light via the inks used. The result is that, for example, the display red is not the same as the hardcopy red. In Fig. 1 the particular gamuts of a particular video display (phosphor set) and a particular ink and paper system are shown. The diagram shows that there are large areas of union between the two gamuts, but there are also non-neglible areas of disunion. If a color from the video gamut is not within the hardcopy gamut, i.e., unreachable, it has to be represented by a color that is within the hardcopy gamut. All unreachable colors may be collapsed to the closest reachable color, which throws away discriminability; the video gamut may be limited so no color is specified that cannot be matched, which is probably unacceptable; the larger gamut may be compressed into the smaller one through some sort of scaled mapping, which discards the possibility of a match entirely; or some reachable color may be substituted for any unreachable one, while endeavoring to match all reachable ones as accurately as possible. What is desired is a way to implement the latter choice by reducing the lightness, i.e., the normalized brightness, partly down to a point at which the chroma can be reached, and then reducing the chroma until the lowered lightness can be reached.

However, even if the prmary colors are matched, the whites are not. The video white is normally very different in chromaticity from a white copy sheet viewed under usual room lighting. In terms of correlated color temperature the video white is likely to lie between 6500 and 9500 degrees Kelvin, while that of the sheet is easily under 4000. In visual terms the video white is quite blue relative to the white of the sheet. It is not desirable to have the white areas of an image rendered as a robins-egg blue in the copy.

There is a phenomenon that has relevance to the above problem: if a person looks at a colored picture under bright, indirect sunlight, and then at the same picture under only incandescent lighting, the correlated color temperature change in the light sources is from 6500 degrees down to 2600 degrees. The white areas in the picture do not look robins-egg blue outdoors, nor do they look canary yellow indoors, although that is approximately the magnitude of the colorimetric change in those areas for the two conditions. This phenomenon is akin to color constancy, i.e., over a broad range a person continuously redefines white as some kind of average over all areas in view.

What is desired is a method for weighting the intensities of the phosphor primaries so that when combined in even levels, and evaluated with color matching functions, they yield the chromaticity coordinates of the neutrals to which they are to be matched, rather than the actual coordinates of the video white.

With respect to the hardcopy device, present ink-jets do not afford control of dot size. Thus halftoning, used to produce color in the printing industry, cannot be done with ink-jets. Fractional area coverage, for a particular ink, is only achieved by defining some number of addressable points, normally a square array, and then determining at how

many of them to place a dot. This is done by developing a square array of numbers with the same number, N, of elements per side as the array of addressable points to be used. The array of numbers contains every number from 0 to N**2-1, and the numbers are positioned in the array so that as the pattern is filled the dots on paper are as uniformly distributed as possible.

A fixed relationship is established between the numeric array and addressable points. At each addressable point the fractional area coverage desired is obtained for each ink, the value is multiplied by N**2, the product is rounded, and the result is added to the array number corresponding to the particular addressable point. If the sum is greater than N**2-1, a dot is printed at that point, otherwise not. This results in optimum shading of the paper, in preservation of the maximum contrast edges at the full resolution of the system, and in correct location and continuity of the lower contrast edges though with increasing loss of acutance as contrast is lower. When placement has been determined for the ink dots, the resulting color is calculated by a method analogous to that used for the phosphor outputs. The contributions for each surface color are weighted by the fractional area it covers since there is no variation in intensity. However, the ink dots cover more than the addressable points, and therefore there is more color than desired. This implies that a correction for oversized dots must be performed to get a good color match.

Summary of the Invention

Accordingly, the present invention provides a color transformation algorithm for matching hardcopy color to display color to take account both of the limitations of video color and of the imperfect character of the colorants in the inks used. The video red-green-blue (RGB) is normalized and converted into chromaticity coordinates in XYZ color space. The hardcopy system is reduced to a well-behaved system (MSW) which can be solved explicitly by restricting the hardcopy colors to some percentage of one of the binary mixtures of inks, some percentage of one of the single inks, and some percentage of copy white. The data in XYZ color space is converted to this MSW space. Unreachable colors are mapped into reachable colors. Correction for hardcopy non-linearities is accomplished by distorting the calculated ink amounts using a function derived from measurement of the dot characteristic. A coverage ratio is used to correct for color shifts. The result is cyan-magenta-yellow (CMY) values representing the hardcopy color which matches the video color. For copiers requiring an RGB input, the bits of the CMY values are complemented. The resulting color is sent to a dithering algorithm to convert these percentages into dots on paper.

The objects, advantages and novel features of the present invention will be apparent from the following detailed description when read in conjunction with the appended claims and attached drawing.

Brief Description of the Drawing

Fig. 1 is a plot of the comparison of a video diplay gamut and a hardcopy gamut in a CIE (XYZ) chromaticity space.

Fig. 2 is a flow chart showing the sequence of events for matching video color and hardcopy color.

Figs. 3a and 3b are a block diagram flow chart for matching video color and hardcopy color corresponding to Fig. 2.

Description of the Preferred Embodiment

Referring now to Figs. 2 and 3 and Appendix I the first step in matching hardcolor copy is to convert the video RGB data from the color map of a display device into a standard C.I.E., or XYZ, space. To define a given color using three primary colors, such as red, green, blue, the value of one of the primaries may be negative. The Commission International de L'Eclairage (CIE), or International Commission on Illumination, in 1931 defined a transformation so that in a new color coordinate system all the components, X, Y, and Z have positive values. The C.I.E. diagram is a generally horseshoe-shaped spectrum locus 12 in a plane Cartesian XY coordinate system on which points representing the chromaticities of the spectrum colors are plotted according to their wavelengths in nanometers. The Z-axis, orthogonal to the XY plane, determines the luminance of the color. A triangle 14 represents the video display gamut, i.e., the colors which can be displayed by a particular three primary color system, such as the NTSC phosphor-set commonly used for color video display devices. An irregular polygon 16 represents the colors which can be displayed by a hardcopy device, such as an ink-jet printer with cyan-magenta-yellow (CMY) and black inks and a particular paper.

The RGB data is in the form of n-bit words from the color map of the video display, i.e, an integer value between 0 and 2**n)-1. This data is normalized to a range of 0-1.0 with compensation for the video gamma. As is shown in Fig. 1 the hardcopy, or paper, white 18 is not the same as the video display white 20. Therefore, the video display white 20 when mapped into the XYZ color space and then converted to the hardcopy produces a greenish color. Thus, the conversion from RGB space to XYZ space first involves weighting the conversion matrix so that the video and hardcopy whites are coincident, i.e., unit values of RGB in video white are treated as though they produced paper white to insure that neutral colors on the video display print as neutral colors on the hardcopy/device. Now the data is converted from RGB space to XYZ space via a 3x3 matrix multiply:

$$[A]*[R,G,B]=[X,Y,Z] \quad (1)$$

where the parameters of the matrix multiplier A are based upon measured data for the particular phosphor set as weighted to produce white coincidence.

To convert from XYZ space to the hardcopy space involves eight unknowns, namely the three components of RGB space, the three components of CMY space, white and black. The Neugebauer equations for XYZ space are defined as:

$$X=K_cC + K_mM + K_yY + K_rR + K_gG + K_bB + K_wW$$

$$Y=K_cC + K_mM + K_yY + K_rR + K_gG + K_bB + K_wW \quad (2)$$

$$Z=K_cC + K_mM + K_yY + K_rR + K_gG + K_bB + K_wW$$

However, in a registered-dot ink-jet hardcopy device combination colors (RGB) are formed by the super-position of two of the CMY components on top ofeach other. Therefore, if the dominant hue of a particular color is, for example, green, the R and B components can be ignored. Likewise, if the greenish color is more blue than yellow, then the M and Y components also can be ignored. This reduces the Neugebauer equations to:

$$\begin{aligned} X&=K_cC + K_gG + K_wW \\ Y&=K_cC + K_gG + K_wW \\ Z&=K_cC + K_gG + K_wW \end{aligned} \quad (3)$$

Thus, by restricting the choices to the most likely choice of RGB and the most likely choice of CMY, the Neugebauer equations are reduced to a set of three equations with three unknowns and can be solved explicitly rather than iteratively. Since the RGB component is a mixture (M) of two of the CMY components, the CMY component is a single (S) color, and white (W) remains, this new color space is referred to as the MSW space, and

$$[X,Y,Z]=[K]*[M,S,W] \quad (4)$$

or

$$[M,S,W]=[K]^{-1}*[X,Y,Z] \quad (5)$$

The next step is to convert the XYZ color space to the MSW color space. There are six possible combinations of the RGB components:

$$\begin{aligned} &R \geq G \geq B \\ &R \geq B \geq G \\ &G \geq R \geq B \\ &G \geq B \geq R \\ &B \geq R \geq G \\ &B \geq G \geq R \end{aligned} \quad (6)$$

Based upon the relative magnitudes of red, green and blue in the video display data, an initial one of the six possible color correction matrices is selected to perform the conversion. Thus, each color correctionmatrix corresponds to some region of RGB values. For colors near the borders of these

regions the initial matrix selection may be incorrect, which leads to negative values in the mixed or single components. Since a "negative" dot cannot be printed, the useful solution consists only of positive values. When a negative value occurs, the next closest matrix is selected and the XYZ to MSW conversion is performed again. Most of the time the initial matrix yields all positive values for the mixed and single components. Using the all positive result black is determined by the difference between a unit area and the mixed, single and white areas:

Black = 1.0 -M -S -W (7)

Since the conversion from XYZ space to MSW space involves a 3x3 matrix multiplication,

[B][X,Y,Z] = [M,S,W] (8)

and the conversion from RGB space to XYZ space also involves a 3x3 matrix multiplication, a direct conversion from RGB space to MSW space may be used:

[A][B][R,G,B] = [M,S,W] (9)

However, since both RGB space and MSW space are referenced to a common XYZ space, the XYZ space serves to isolate the video color world from the hardcopy color world. Also, as is discussed infra, XYZ space is used to restore any differentiation that may be lost.

If the white component of MSW space is negative, the requested color is too saturated and cannot be reproduced on the hardcopy. The negative white values are set equal to zero. This is equivalent to an unreachable color 22 which exists within the video color gamut 14, but outside the hardcopy color gamut 16. The zeroing of the white acts to pull the color in along a line 24 connecting the hardcopy white 18 to the unreachable video color 22 until the perimeter 26 of the hardcopy color gamut 16 is attained. This line 24 is called the dominant wavelength of the color, and the dominant wavelength of the color is maintained while its saturation is decreased.

After all negative values have been corrected, the corrected, or compensated, MSW components [M', S', W',] are summed. If the sum exceeds 1.0, the requested color is brighter than the hardcopy device can achieve under the illuminant selected. In this situation the components are normalized by dividing each component by the sum, making the sum of the components less than 1.0. Now the resulting MSW components [M",S",W"] is a reachable color for the hardcopy device. However, because of the above compensations for the unreachable colors, colors which are different in color or brightness on the video display are matched as the same color on the hardcopy device.

Therefore, the next step is to restore the shading or edge between adjacent colors, i.e., the distinction between adjacent colors. This is accomplished by calculating a new Y component for the MSW space by using the inverse matrix of the XYZ to MSW conversion matrix:

$[A^{-1}][M",S",W"] = [X',Y',Z']$ (10)

Then the quantity (Y'-Y) is calculated. If Y' = Y, then there is an exact match of the hardcopy and videocolors, i.e., the color is within the coincident portion of the respective gamuts. If Y' is greater than Y, resulting from the correction for the negative white, than black is added by computing a scale factor, based on the difference between Y and Y', and applying the scale factor to the mixed and single components. Black is the remainder when MSW components are subtracted from 1.0, generally given as follows:

Black = $1.0 -(M_f + S_f + W_f)$ (11)

wherein for this specific case W_f by definition is zero since white was negative. This has the effect of adding black ink to pull the brightness down. If Y' is less than Y, resulting from the component sum being greater than 1.0, white is added by calculating a scale factor, based upon the difference between Y and Y', to be applied to the mixed and single components. The white component is then set equal to the remaining area after the mixed and single component is subtracted out:

$W_f = 1.0-(M_f + S_f)$ (12)

While the previous two steps, equations (10) and - (11), preserve the luminance differences between unreachable colors at the expense of chromaticity matches, this step increases the luminance of the color while decreasing its saturation. The final MSW vector has components which match the color exactly where the video and hardcopy gamuts are coincident, which match the color to a reachable color if the color is within the video gamut but outside the hardcopy gamut, and which match the color into colors which preserve the difference between colors.

The next step is to determine what inks to put down on the paper, i.e., convert the MSW components into CMY components. The assignment of values for the inks depends upon the particular

MSW conversion matrix used. One of the inks, the single component such as the cyan (C) shown in equations (3), appears everywhere ink is laid down. The value of this ink is:

C_{max} = 1.0 -W_f (13)

A second ink occurs in both the mixed component and black and has a value:

C_{mid} = B_f + M_f (14)

where B_f is the black. The mixture of C_{max}+C_{mid} produces the mixed component shown as green (G) in equations (3). The third ink appears only in the black:

C_{min} = B_f (15)

The CMY values, C_{max}, C_{mid} and C_{min} represent the percentages of each ink to be used for a given color for a registered-dot ink-jet hardcopy device, i.e., where the mixed and black components are formed by overlaying dots of ink on top of each other.

These CMY percentages do not represent a uniformly applied amount of ink with variable optical density, but rather the fraction of discrete drops to be deposited over some area of the paper. The correct color sensation is produced because the visual system averages this pattern of dots. Because the ink dots overlap, this visual sensation is not linear with the number of dots in the pattern. To handle this irregularity the CMY values are used as indices to hardcopy gamma correction lookup tables, based upon measurements containing new values which compensate for the system irregularities. Since black is usually a separate ink rather than a combination of the three color inks, a black gamma correction table is used to compensate for C_{min}.

For C_{mid} two difficulties arise. First, when C_{max} and C_{mid} are combined, the amount of dot overlap is different due to the wetting of the paper surface by the first ink laid down. This results in a gamma correction characteristic of the binary mixture which differs from the gamma correction characteristics for the individual inks. Therefore, C_{mid} is processed using a mixture gamma correction table (red, green or blue) rather than a single ink gamma correction table. Second, the prior gamma correction of C_{min} leads to noticeable shifts since after gamma correction through their respective tables the percentage coverage of C_{mid} by C_{min} changes. To avoid this problem a coverage ratio is computed from the original, uncorrected values as:

C.R. = (C_{mid}-C_{min})/(1-C_{min}) (16)

The gamma corrected value of C_{min} is then used as an index to the inverse of the C_{mid} gamma correction table to yield a base value. A corrected value for C_{mid} is then computed as:

C_{mid} = base+(C.R.)*(1-base) (17)

As an example, if the value for C_{mid} is 1/2 and for $C_{min}$is 1/4, then 50% of the C_{mid} covers C_{min}. Then if the gamma correction is C_{mid} = 3/8 and C_{min} = 1/8, now only 33% of the C_{mid} covers C_{min}resulting in more color than desired. The color ratio serves to restore the appropriate ratio after gamma correction.

Likewise for C_{mid} and C_{max}:

C.R.' = (C_{max}-C_{mid})/(1-C_{mid}) (18)

C_{max}' = base'+C.R.'*(1-base') (19)

Where base' is determined by inverse gamma transformation of gamma-corrected C_{mid} through the appropriate CMY (single color) gamma-correction table. C_{max}' is then gamma corrected through the appropriate CMY table. This produces a new CMY vector [C',M',Y'] which may be output to a hardcopy device, or complemented to determine a new RGB vector [R',G',B'] for those devices which require an RGB input. The output of the color matching algorithm is then processed by an appropriate dithering algorithm to convert the resulting color data into drops of ink on the paper.

Thus, the present invention provides a method for matching video color to hardcopy color by replacing video RGB with hardcopy RGB which compensates for he effects of video gamma, paper, and ink by use of a new MSW space, and which compensates for the ink-jet gamma by appropriately chosed gamma correction tables together with using a coverage ratio for interaction of the inks.

Claims

1. A method for matching hardcopy color to video display color comprising the steps of:

transforming normalized video color data into MSW color data where MSW color data has a binary mixture component, a single component and a white component;

manipulating said MSW color data to convert un-

reachable video color data into reachable hardcopy color data; and

converting said manipulated MSW color data into hardcopy color data.

2. A method as recited in claim 1 wherein said converting step comprises the steps of:

computing a coverage ratio to compensate for interactions between components of said hardcopy color data; and

using said coverage ratio to determine new values for said components of said hardcopy color data.

3. A method as recited in claim 1 wherein said transforming step comprises the steps of:

transforming said normalized video color data into XYZ space where all color components have a positive value; and

tranforming color data in said XYZ space into said MSW color data.

4. A method as recited in claim 3 wherein said transforming into XYZ space step comprises the step of weighting the conversion matrix to be used so that video and hardcopy color whites are coincident.

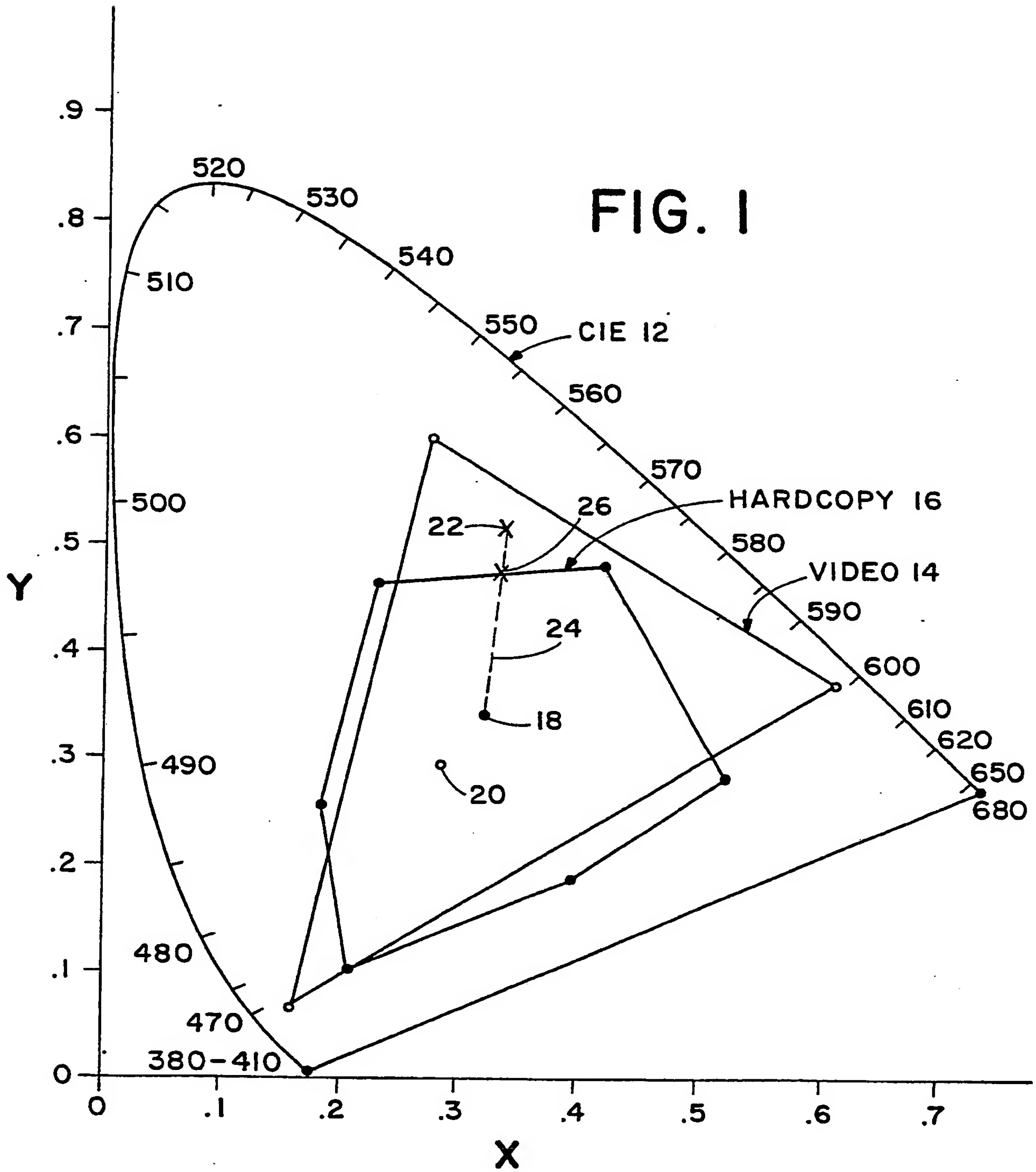
FIG. I
Y
X
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.1
.2
.3
.4
.5
.6
.7
520
530
540
550
560
570
580
590
600
610
620
650
680
510
500
490
480
470
380-410
CIE 12
HARDCOPY 16
VIDEO 14
22
26
24
18
20

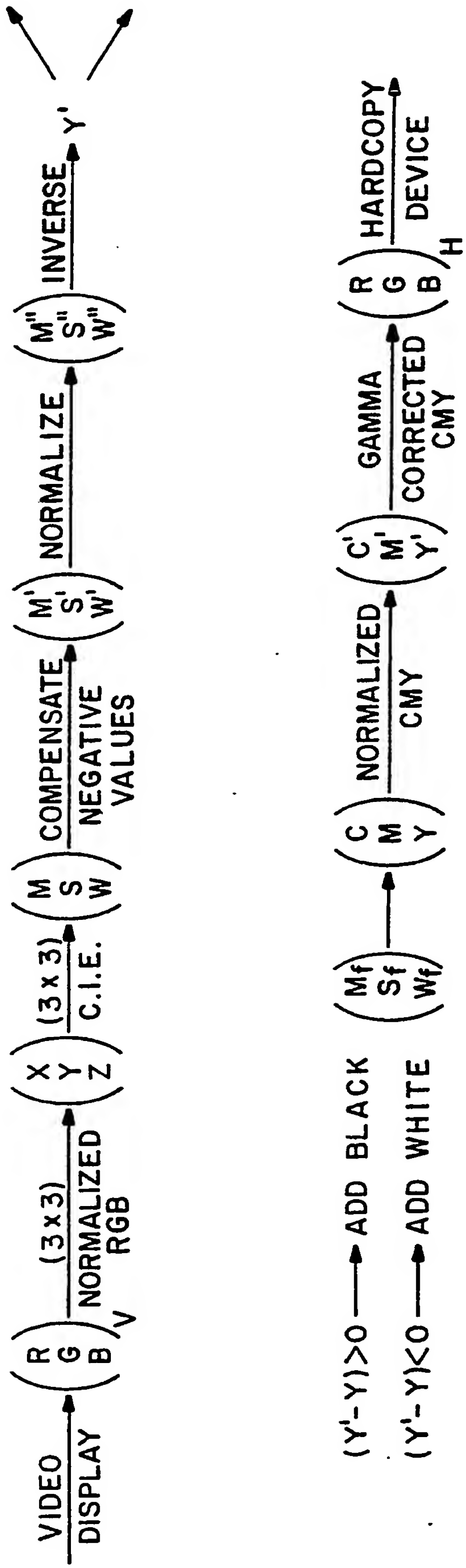
VIDEO DISPLAY
R G B V
(3x3) NORMALIZED RGB
X Y Z
(3x3) C.I.E.
M S W
COMPENSATE NEGATIVE VALUES
M' S' W'
NORMALIZE
M" S" W"
INVERSE
Y'
(Y'-Y)>0 ADD BLACK
(Y'-Y)<0 ADD WHITE
Mf Sf Wf
C M Y
NORMALIZED CMY
C' M' Y'
GAMMA CORRECTED CMY
R G B H
HARDCOPY DEVICE

FIG. 2

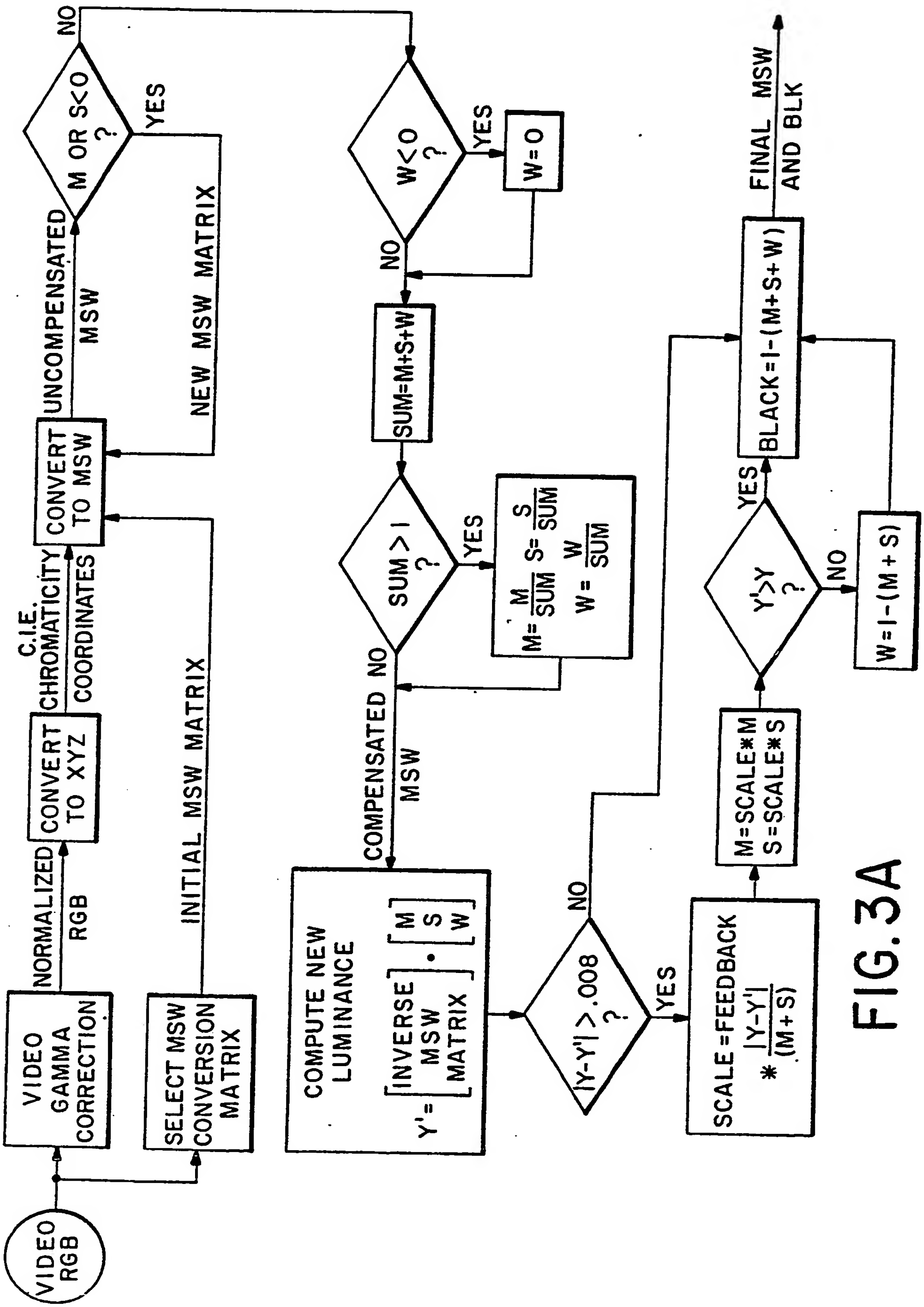
VIDEO RGB
VIDEO GAMMA CORRECTION
SELECT MSW CONVERSION MATRIX
NORMALIZED RGB
CONVERT TO XYZ
INITIAL MSW MATRIX
C.I.E. CHROMATICITY COORDINATES
CONVERT TO MSW
UNCOMPENSATED MSW
M OR S<O ?
YES
NO
NEW MSW MATRIX
W<O ?
YES
W=O
NO
SUM=M+S+W
SUM>I ?
YES
M= M/SUM S= S/SUM W= W/SUM
NO
COMPENSATED MSW
COMPUTE NEW LUMINANCE
Y'= [INVERSE MSW MATRIX] · [M S W]
|Y-Y'|>.008 ?
NO
YES
SCALE=FEEDBACK * |Y-Y'| / (M+S)
M=SCALE*M S=SCALE*S
Y'>Y ?
YES
NO
W=I-(M+S)
BLACK=I-(M+S+W)
FINAL MSW AND BLK

FIG.3A

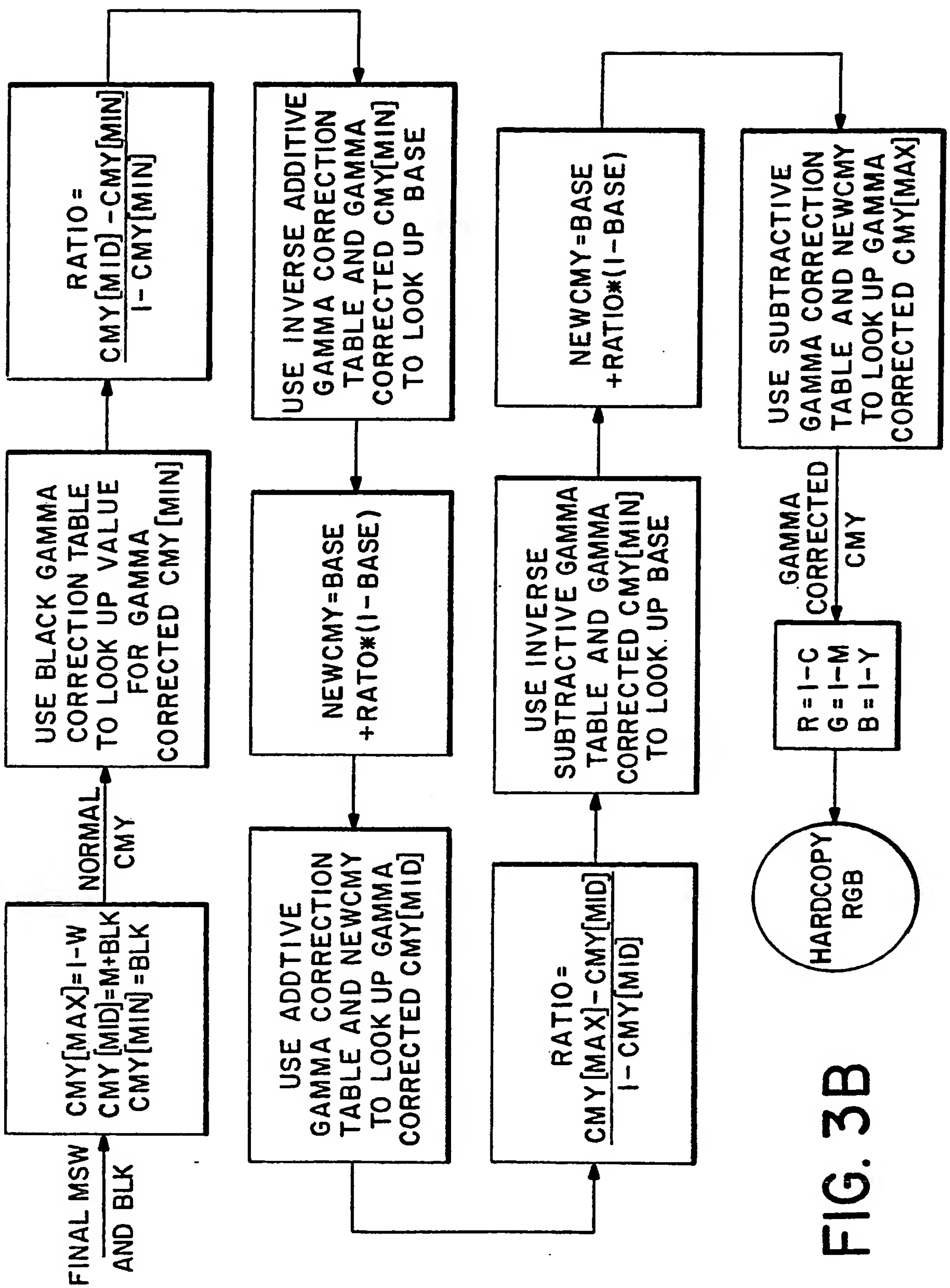
FINAL MSW
AND BLK
CMY[MAX]=1-W
CMY[MID]=M+BLK
CMY[MIN]=BLK
NORMAL
CMY
USE BLACK GAMMA CORRECTION TABLE TO LOOK UP VALUE FOR GAMMA CORRECTED CMY[MIN]
RATIO = CMY[MID] - CMY[MIN] / 1 - CMY[MIN]
USE INVERSE ADDITIVE GAMMA CORRECTION TABLE AND GAMMA CORRECTED CMY[MIN] TO LOOK UP BASE
NEWCMY=BASE +RATO*(1-BASE)
USE ADDTIVE GAMMA CORRECTION TABLE AND NEWCMY TO LOOK UP GAMMA CORRECTED CMY[MID]
RATIO = CMY[MAX]-CMY[MID] / 1-CMY[MID]
USE INVERSE SUBTRACTIVE GAMMA TABLE AND GAMMA CORRECTED CMY[MIN] TO LOOK UP BASE
NEWCMY=BASE +RATIO*(1-BASE)
USE SUBTRACTIVE GAMMA CORRECTION TABLE AND NEWCMY TO LOOK UP GAMMA CORRECTED CMY[MAX]
GAMMA
CORRECTED
CMY
R=1-C
G=1-M
B=1-Y
HARDCOPY
RGB

FIG. 3B